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MEASUREMENT OF OXYGEN CONSUMPTION USING THE CANADIAN CLEARANCE DIVING APPARATUS (CCDA)

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Table of Contents

List of Figures ii
Abstract iii
Introduction 1
Methods 2
Results 4
Discussion 5
Conclusions and Recommendations 6
References 7

List of Figures

Figure 1. Exercise schedule. 8
Figure 2. Sample stripchart recording. 9
Figure 3. Mean $\dot{V}_{O_2}$ *vs.* workload for three experimental conditions. 10
Figure 4. Comparative changes in work with condition. 11
Figure 5. Comparative average $\dot{V}_{O_2}$ for dry subjects. 12
Figure 6. Comparative average $\dot{V}_{O_2}$ for wet subjects. 13

ABSTRACT

The Canadian Clearance Diving Apparatus (CCDA) was modified to serve as a 100% oxygen rebreathing system for the measurement of oxygen consumption ($\dot{V}_{O_2}$) in water. Four physically active male subjects each performed three exercise tests on an electromagnetically-braked bicycle ergometer: in shorts on dry land; in shorts while submerged; and in wet suits while submerged. Mean $\dot{V}_{O_2}$ for dry exercise was significantly less than mean $\dot{V}_{O_2}$ for either wet condition. The mean $\dot{V}_{O_2}$ values for the two wet conditions were not significantly different, but no subject was able to complete the work protocol in wet suits. It was suggested that the constrictive nature of the wet suit restricted blood flow to the muscles, thereby reducing the removal of metabolic waste products and the supply of oxygen, leading to an increase in muscle fatigue. Comparison of the results with standard values and results obtained using the Low Resistance Breathing Apparatus (LRBA) indicated that the CCDA is a viable system for the measurement of $\dot{V}_{O_2}$ in water.

INTRODUCTION

In semi-closed circuit underwater breathing apparatus (SCCBA) the oxygen partial pressure of the inhaled gas depends on oxygen consumption ($\dot{V}_{O_2}$) of the diver. When evaluating the performance of an SCCBA, the investigators require knowledge of $\dot{V}_{O_2}$ for the subjects performing the exercise as well as maximal requirements during operational diving. Often the only method of obtaining this data is through prior measurements during similar exercises. Unfortunately, although a number of methods exist to measure $\dot{V}O_2$ under dry conditions, the application of these methods in water has been difficult. Any apparatus proposed to measure oxygen consumption in water must be resistant to the ingress of water, and must take into account and control hydrostatic pressure differentials between the respiratory tract and ambient pressure. Further, it must allow for the increase in breathing effort per unit volume that occurs as a result of depth-related increases in gas density. If volume is to be measured, the apparatus must also be insensitive to both pressure and gas composition (Lecourt, 1986; Fairburn *et al*, 1988).

A number of systems have been proposed and tested. The Low Resistance Breathing System (LRBS) developed at the State University of New York in Buffalo utilized a bag-in-a-box concept (Thalmann *et al*, 1978). The Low Resistance Breathing Apparatus (LRBA) (Lecourt, 1986), and the diver-portable version of the LRBA, the Underwater Metabolic Assessment System (UMAS) (Fairburn *et al*, 1988), developed at the Defence and Civil Institute of Environmental Medicine (DCIEM) were open-circuit, compressed-air systems based upon the principles used in the LRBS. In the LRBA and UMAS, the subject inspired gas from a bag, and expired air into a mixing chamber. Samples were drawn from the mixing chamber for analysis of carbon dioxide and oxygen levels. A small turbine flowmeter was used to measure the volume of expired gas as it exited the mixing chamber. The bag, mixing box and volume meter were enclosed in a housing. A compensation system on the exhaust side of the breathing apparatus maintained ambient pressure inside the housing, plus or minus a hydrostatic component. Although dry condition testing of the UMAS proved satisfactory (Fairburn *et al*, 1988), technical difficulties - in particular, ingress of water into the apparatus housing at the exhaust point - were experienced while testing the system for underwater work. The water posed no danger to the subject, but did create a potential for instrument damage. In principle, then, the UMAS is still feasible, but a more technologically advanced solution is required to make it functional. Coincidentally, a similar need exists in the DCIEM Aerospace Group (AG). The group has produced a proposal for a pressure control device that could be used with the UMAS

to eliminate the water-ingress problem.

The AG's pressure control system will not be available in the near future, consequently, an alternative metabolic measurement technique for underwater use was required. A technique used in the past (Donald and Davidson 1954) involves 100% oxygen rebreathing, in which the diver breathes pure oxygen and the pressure drop at the oxygen tank is monitored. The pressure differential over a given time interval is used to calculate oxygen consumption:

$$\dot{V}_{O_2}=N(P_1-P_2)/\Delta t$$

where $\dot{V}_{O_2}$ represents oxygen consumption, $(P_1 - P_2)$ the tank pressure differential over a given period of time (Δt), and N the volume of O_2 in tank per unit pressure. Although the system is simple and may be diver-portable, its application is limited by the toxic effects of oxygen breathed at pressures of 2 atmospheres, absolute, or more (Dwyer 1977).

In this experiment, a modified version of the Canadian Clearance Diving Apparatus (CCDA) was used as a 100% oxygen rebreathing system for measuring oxygen consumption. The validity of the technique was assessed by comparison of results with those of other systems. Further, the data was analyzed for the effects on $\dot{V}_{O_2}$ of the increased viscous resistance imposed by water and by wearing a constrictive clothing ensemble, specifically a wet suit.

METHODS

Subjects. Four male Canadian Forces Clearance Divers volunteered for the experiment. Their physical characteristics are presented in Table 1.

TABLE 1: PHYSICAL CHARACTERISTICS OF SUBJECTS

Subject	Age (yrs)	Weight (kg)	Height (cm)
1	34	99.8	185.4
2	35	99.8	180.3
3	27	70.3	170.2
4	36	81.6	175.3

Apparatus. All trials took place in the Dive Chamber of the DCIEM Diving Research Facility (DRF). The subjects exercised on an electromagnetically-braked

bicycle ergometer (W.E. Collins, Pedalmate).

The CCDA was modified to serve as the breathing system - a single oxygen bottle was used, and the CCDA was placed on straight demand. The subject used the bypass valve to fill the counter-lung as required, then breathed from the counter-lung. The pressure drop in the oxygen cylinder was measured using a high pressure sampling line (Parker PARFLEX N, Nylon 11 tubing, 0.318 cm outer diameter, 0.079 cm wall thickness, approximately 8 m long). The line was attached between the high pressure port of the CCDA regulator, and a pressure transducer (Schaevitz, type P1021-005) connected to a chart recorder (Gould, recorder 2600). A sample line was connected to the exhalation side of the mouthpiece to measure breathing frequency, but the results were not reported. Temperature of the ambient conditions was measured by a thermistor (YSI, type 44004) and digital thermometer (Doric, 450-TH). The gas in the bottle was assumed to be at the same temperature as the surroundings.

Procedure. Three experimental conditions were used - dry, wet/shorts and wet/wet suit. For the dry condition, the subjects wore shorts, t-shirts and running shoes. In the wet/shorts condition, the same ensemble was worn, but the running shoes were replaced with wet suit booties. A wet suit, including booties but lacking gloves, was worn for the wet/wet suit condition. To maintain subject comfort and control for thermal effects air temperature was (±SD) 20.9±0.5°C in the dry condition, 29.0±0.5°C in the wet/shorts condition, and 9.7±0.2°C in the wet/wet suit condition.

During the dry trials, the water was drained from the chamber. The breathing apparatus was suspended in front of the subject, such that the subject did not perform the extra work required to support the apparatus. A noseclip was employed to minimize gas losses through the nose.

During the wet trials in the Dive Chamber, a harness was worn to anchor the subject to the ergometer. Weightbelts and 1.5lb ankle weights were also used to counteract buoyancy. A face mask was worn for all wet trials. To minimize gas losses, the subjects were requested not to clear their mask, or exhale through their nose. If escaping gas was observed during the trial, divers were reminded not to exhale through the nose. This system was effective, since the face mask provided a good seal that prevented water ingress and created resistance to nasal gas flow.

Each subject performed three trials on three successive days, in the following order - dry, wet/wet suit, and wet/shorts. Presentation of conditions could not be randomized due to limited availability of the Dive Chamber.

To perform the experiment the subject started breathing from the CCDA, emptied the counterlung, and filled it with oxygen using the bypass valve. In the dry condition the subject then started exercising on a set cue. In both immersed conditions, the subject entered the water and strapped himself onto the ergometer, then began exercising on the set cue. The exercise protocol, Figure 1, was the same as that used in Lecourt (1986). The initial ergometer setting was 50 watts. The setting was increased by 25 watts after every six minutes until 125 watts was achieved. Exercise was completed on the subjects request or after six minutes of work at 125 watts. The pedal frequency was between 60 and 70 RPM.

Analysis. Pressure drops were converted to volume changes using the equation:

$$\frac{P_1V_1}{T_1}=\frac{P_2V_2}{T_2}$$

where:

P_1 and P_2 = initial and final pressures

V_1 and V_2 = initial and final volumes

T_1 and T_2 = initial and final temperatures

For each workload, the pressure change between the first and last bypasses during the six minute interval was used in the calculation of $\dot{V}_{O_2}$ (Figure 2). The mean and standard deviation of $\dot{V}_{O_2}$ were calculated and plotted against workloads for all three conditions. Regression equations were calculated and used to determine the differences in workload between the three conditions. Analysis of variance with repeated measures was performed using condition and workload as trial factors, and Scheffé's multiple comparison test (Scheffé 1959) was used to locate significant differences.

RESULTS

The mean $\dot{V}_{O_2}$ over all subjects, and one standard deviation about the mean for each workload, are plotted in Figure 3 with the linear regression for each condition. Analysis of variance indicated that both treatment and workload had a significant ($p=0.0008$ and $p=0.0001$, respectively) effect on mean $\dot{V}_{O_2}$. The mean $\dot{V}_{O_2}$ for the dry condition was significantly different from either wet condition (Scheffé critical values 29.83 and 54.37, $S=6.92$ at $\alpha=0.1$ for wet/shorts and wet/wet suit vs. dry, respectively). The mean $\dot{V}_{O_2}$ for the wet/wet suit condition was not significantly different from the mean $\dot{V}_{O_2}$ for the wet/shorts condition (Scheffé critical value 3.65, $S=6.92$ at

α=0.1). Using the regression equations (Figure 3), the difference in $\dot{V}_{O_2}$, at a given workload, between the dry and the wet/shorts conditions translated into a mean increase in workload of approximately 78 Watts (Figure 4). Similarly, the mean increase in workload from the dry to the wet/wet suit condition was about 81 Watts, while the mean increase for the wet/shorts to the wet/wet suit conditions was only 9.0 Watts (Figure 4). No subject was able to complete the 125 W workload in the wet/wet suit condition.

DISCUSSION

For a given ergometer setting, a significantly higher power output was required to maintain pedal frequency in water compared to dry conditions (Figure 4). A further increase in power output was required to maintain pedal frequency at a set workload in a wet suit in water as compared to shorts in water (Figure 4). Although the latter difference was not significant, none of the subjects was able to complete the exercise protocol at the highest workload in wet suits, while no subject experienced difficulty in completing the exercise protocol in shorts while submerged. All subjects complained of a burning sensation comparable to ischemia in the thighs while exercising in wet suits. Blood flow to the quadriceps muscle may increase 5.6 to 18.1-fold in exercise corresponding to 15 - 99% of $\dot{V}_{O_2}$max (Grimby *et al* 1967). It seems likely that the constrictive nature of the wet suit restricted blood flow, reducing the removal of metabolic waste products and the supply of oxygen, and resulting in an increased rate of muscle fatigue.

The dry condition CCDA results were compared with oxygen consumption data from a previous experiment that used the Monark bicycle ergometer, and with a set of commonly accepted values established by Åstrand and Rodahl (1977) (Figure 5). In general, the values were comparable in that over the range of workloads at which the CCDA was tested, the accepted values (Åstrand and Rodahl 1977) were within one standard deviation of the CCDA values. Oxygen consumption values obtained using the CCDA and the LRBA (Lecourt 1986) for exercise in the wet/shorts condition are presented in Figure 6. Again, the values obtained using the two systems were similar, although the LRBA values were consistently below those of the CCDA (Figure 6). It should be noted that different bicycle ergometers were used in the two trials. Actual workload is a function of both pedal frequency and ergometer calibration. The ergometer used in this experiment has been employed for a number of years without calibration, and the pedal frequency of the standard values was not reported. Discrepancies between the standard values and the CCDA values might be attributed to variation in

these factors. Differences in the exercise protocols used in the various experiments might also account for the variability observed in the rates of oxygen consumption.

An analysis of the error inherent in the system was performed, taking into account the instrument errors listed by the manufacturers. For an actual $\dot{V}_{O_2}$ of 0.5 L/min, the measured $\dot{V}_{O_2}$ could vary approximately ±65% from the true value. At 1.5 L/min, the variation dropped to within ±22%, and to within ±10% at an actual $\dot{V}_{O_2}$ of 3.5 L/min. Thus, error inherent in the CCDA system constitutes a final source of differences between the accepted values (Åstrand and Rodahl 1977), and the values obtained using the CCDA, especially at low $\dot{V}_{O_2}$ levels. The pressure drop had the greatest influence on the variation in measured $\dot{V}_{O_2}$. The precision and accuracy of measurement could be improved by using a smaller oxygen bottle. Use of a smaller bottle would result in greater pressure drops per unit time, thereby reducing the error relative to the change in pressure.

CONCLUSIONS AND RECOMMENDATIONS

Overall, the CCDA appears to be a viable system for measuring rates of oxygen consumption in water. To improve the accuracy of the results, it is recommended that the bicycle ergometers be calibrated regularly, and that a smaller oxygen bottle be used to increase the pressure drop per unit time, thereby reducing relative errors in the measurement of oxygen pressure. The system would also benefit from an improved method of recording breathing frequencies. With these changes, it is recommended that the CCDA system undergo validation as a useful method of determining the oxygen consumption of subjects in water. For determination of $\dot{V}_{O_2}$ in open-water dives, the CCDA would be easier to use than a UMAS based method. However, the UMAS like apparatus is required to study regarding variables such as carbon dioxide production and ventilation rates as well as control over respiratory parameters like hydrostatic, elastic, and resistive loading.

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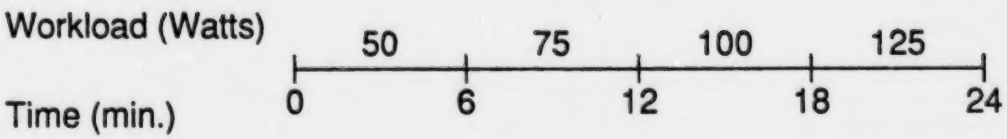

Figure 1. Exercise schedule

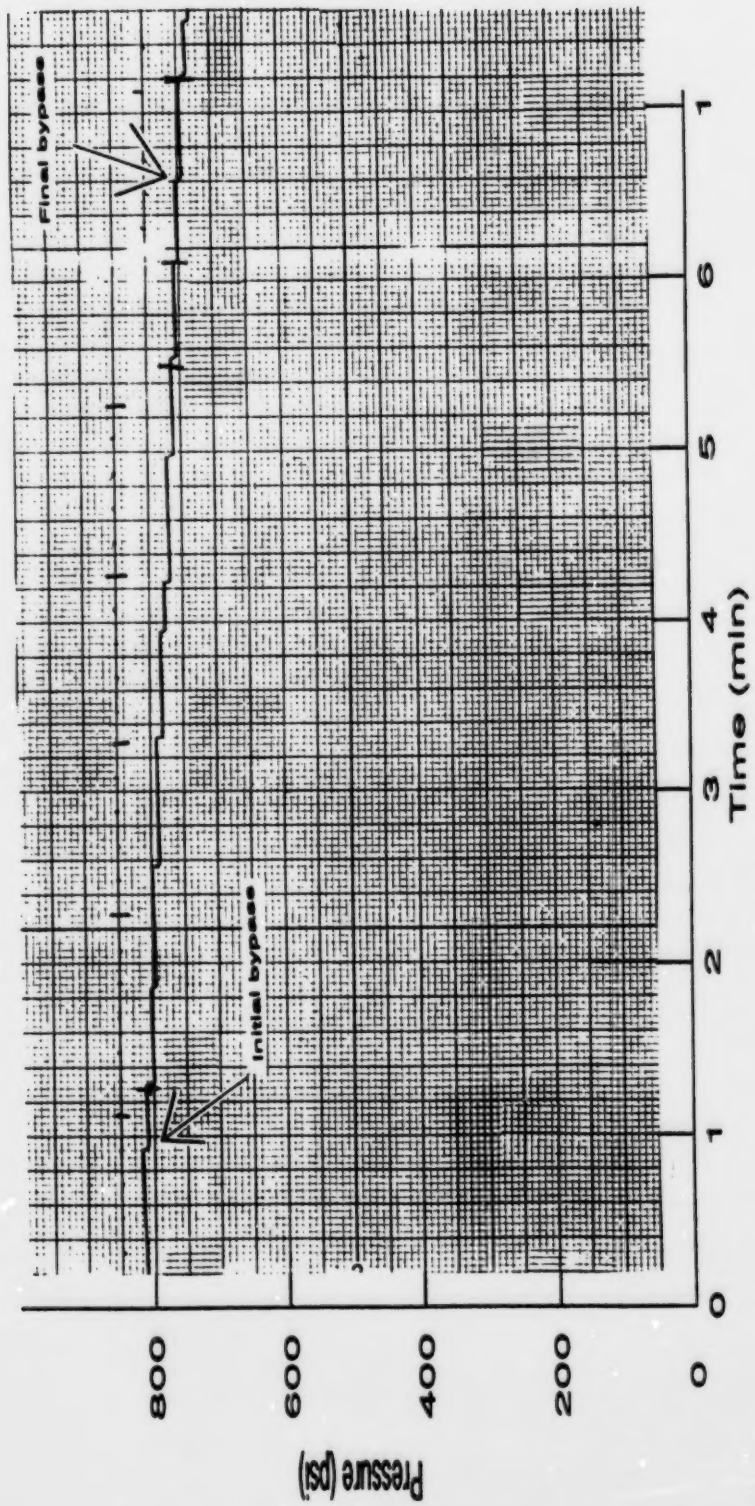

Figure 2. Stripchart section illustrating location of pressure drop used in calculation of oxygen consumption.

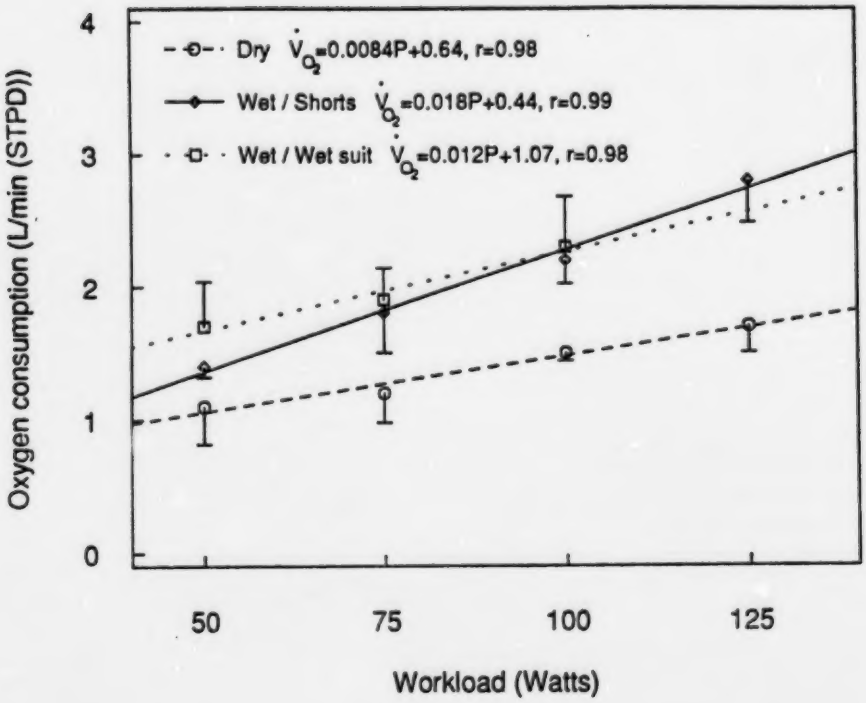

Figure 3. Mean and standard deviations for oxygen consumption in dry and submerged exercise.

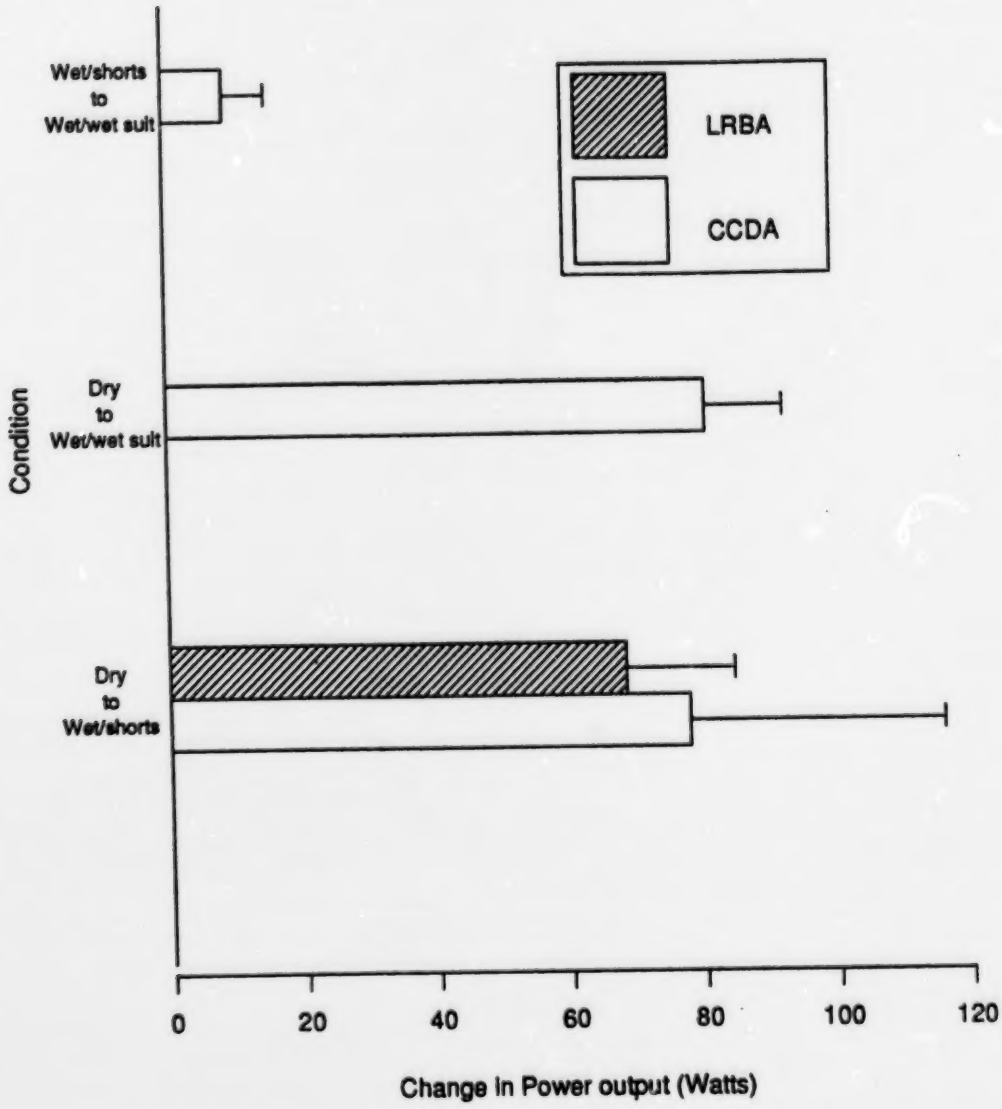

Figure 4. Comparative changes in work with condition. (LRBA value from Lecourt (1986).)

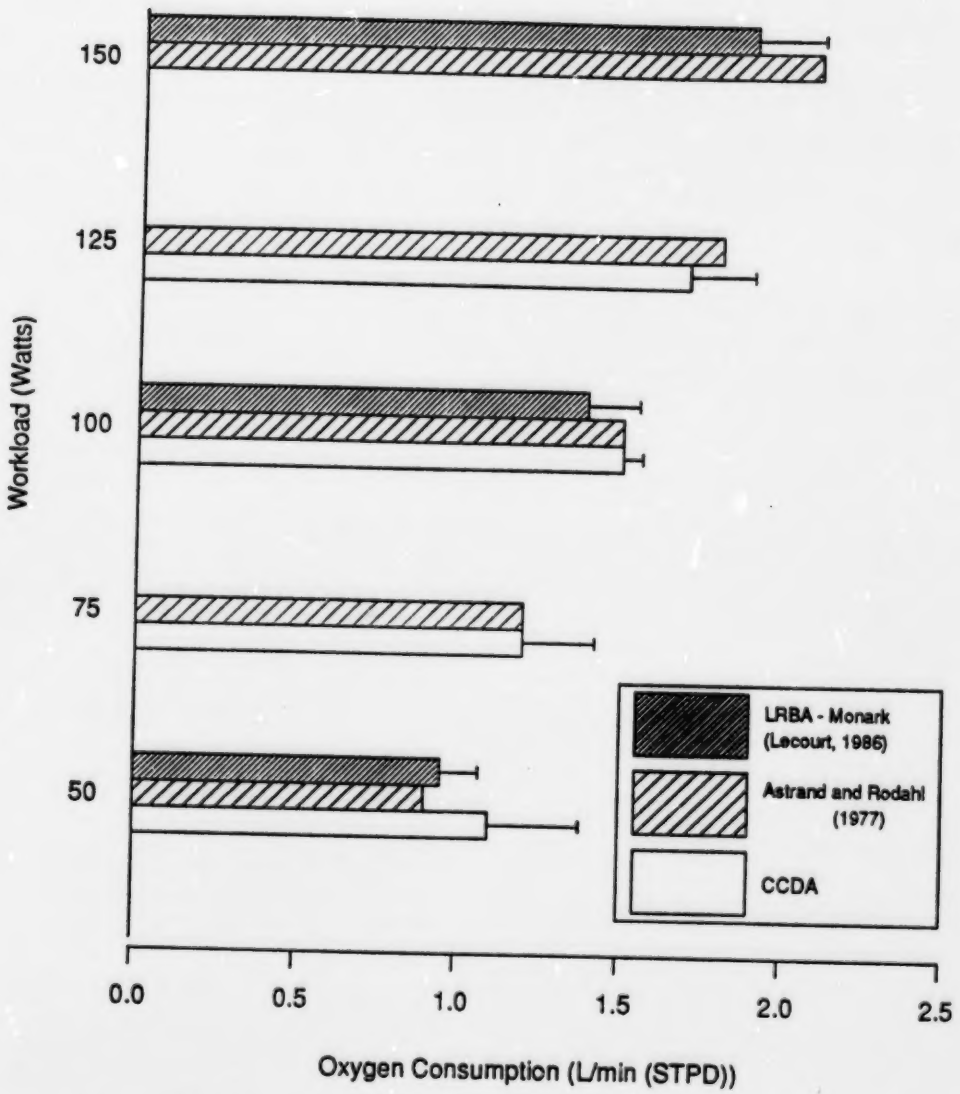

Figure 5. Comparative average oxygen consumptions for dry subjects.

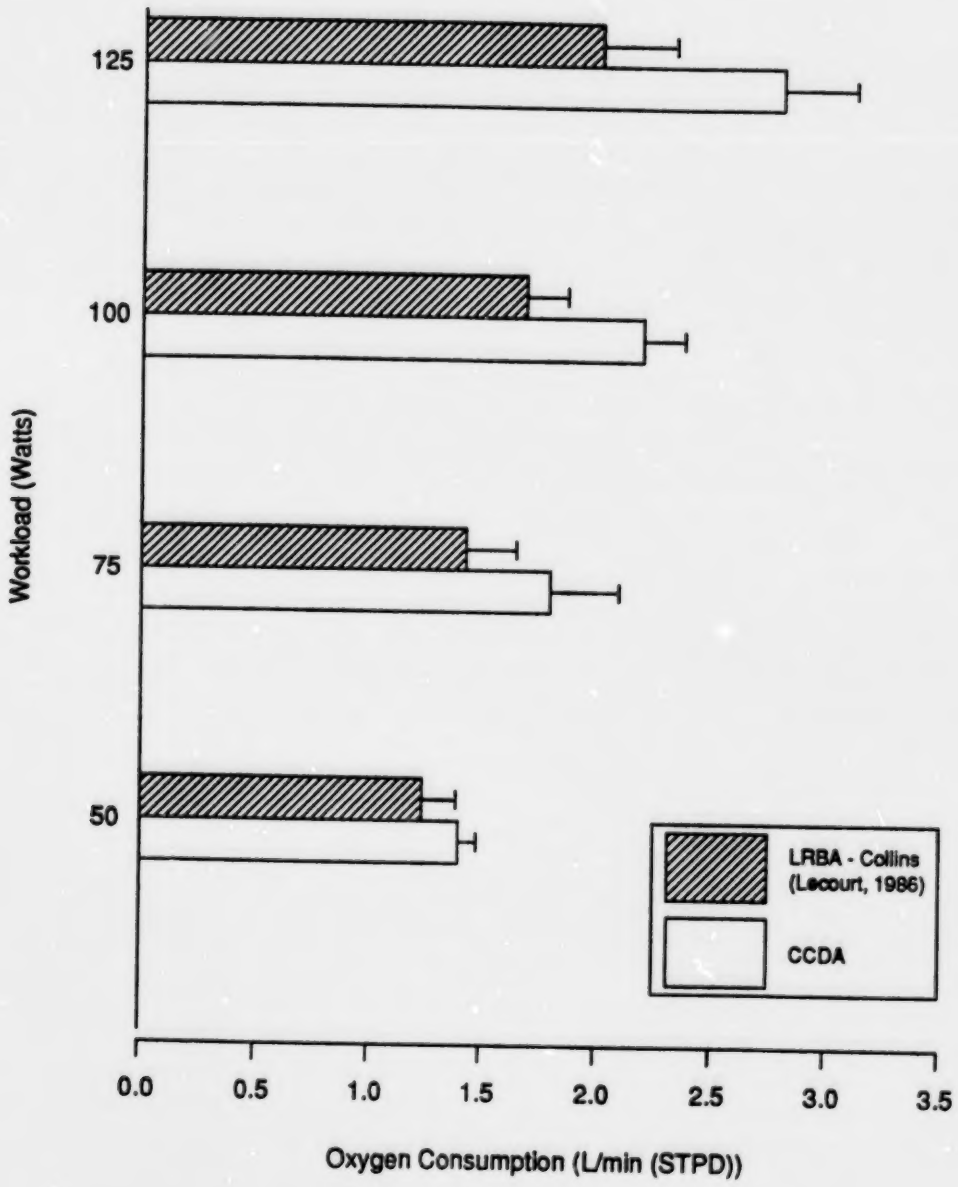

Figure 6. Comparative average oxygen consumptions with submerged subjects

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